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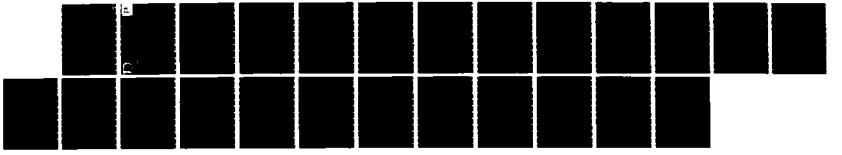

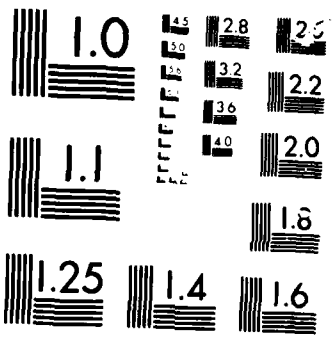
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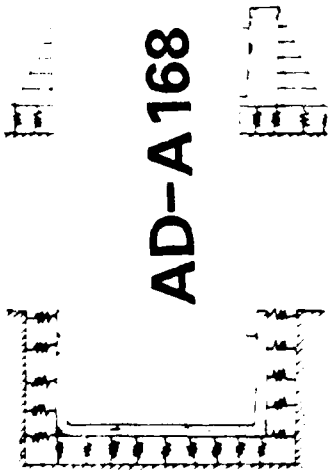
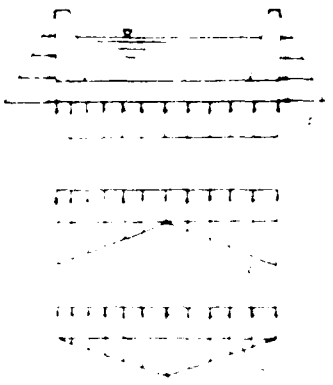




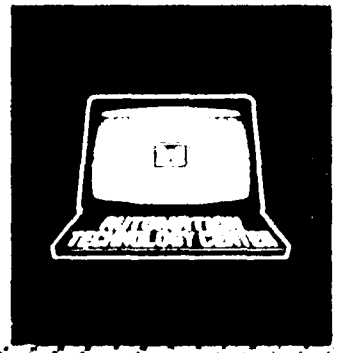
MISCELLANEOUS PAPER ATC-86-1

DESIGN ANALYSES OF U-SHAPED DRY DOCK AND LOCK STRUCTURES: A SURVEY

by

Arnold D. Kerr
University of Delaware
Newark, Delaware 19716

May 1986
Final Report



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Various methods for analyzing U-shaped dry dock and lock structures are covered by this paper. Included are reports of approaches evolving over the last century as were performed in the United States of America (USA), West Germany, and the Union of Soviet Socialist Republics (USSR). These reported investigations deal with the use of analytical models and how they are related to the measurements obtained from actual structures.

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20. ABSTRACT (Continued).

A major problem is the determination of the lateral pressure on lock walls. This is so because the pressure depends on the lock wall movements which are caused by such varied factors as fluctuating water levels and temperatures within the chamber, and densification of the backfill.

The USA publications are more readily available to WES; therefore, the emphasis in this paper is placed on those of Germany and the USSR.

SUMMARY

This paper gives details of a survey of the various methods for analyzing U-shaped dry dock and lock structures as they evolved over the last century. Special emphasis is given to the analytical models used and their relationship to the extensive measurements performed on actual structures in the United States of America (USA), West Germany, and the Union of Soviet Socialist Republics (USSR) during recent decades. It was found that currently there are no generally accepted methods for analyzing the structures under consideration. The main difficulty is the determination of the lateral pressure on the lock walls and how this pressure is affected by the lock wall movements. Such movements are caused by the fluctuating water levels and temperatures within the chamber, which in turn are influenced by the densification of the backfill, among other factors.

PREFACE

This report presents a review of the engineering literature on methods for analyzing U-shaped dry dock and lock structures. The objective of the review was to determine which analytical models are presently being used for analysis of these complex structures. Preparation of the review for this report was accomplished with funds provided to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., under the Civil Works Research and Development program of the Office, Chief of Engineers, US Army (OCE), as part of the Structural Engineering Research Program work unit of the Soil-Structure Interaction (SSI) Studies project.

The report was written by Dr. Arnold D. Kerr of the University of Delaware, under contract DACW 39-84-M-1509-0002 with WES.

Dr. N. Radhakrishnan, Chief of the Automation Technology Center (ATC), WES, and SSI Studies Project Manager, and Dr. Robert L. Hall, Research Civil Engineer, ATC, WES, coordinated and monitored the work. Ms. Gilda Shurden, Publications and Graphic Arts Division, WES, edited the material before publication. Mr. Donald R. Dressler, Structures Division, Civil Works Directorate, was the OCE point of contact.

Director of WES was COL Allen F. Grum, USA. Technical Director was Dr. Robert W. Whalin.

CONTENTS

DESIGN ANALYSES OF U-SHAPED DRY DOCK AND LOCK STRUCTURES: A SURVEY

PART I: INTRODUCTION

1. This miscellaneous paper represents the steps involved in the study entitled "Survey of Analyses for Navigational Lock Structures." Much detail was required for the location and acquisition of relevant papers and reports, as well as the study and write-up of this material. It gives an account of publications that have appeared in the United States of America (USA), West Germany, and Union of Soviet Socialist Republics (USSR). Since the USA publications are known to the Waterways Experiment Station (WES), emphasis is placed on those from Germany and the USSR.

Background

2. The recent approach in West Germany assumes that the base slab rests on an elastic base and the walls are subjected to prescribed earth and water pressure distributions. A thesis by Hilmer (1976) describes this approach.

3. The USSR assumptions are that the walls are attached to a linear Winkler base with a variable coefficient or a nonlinear Winkler base. Gol'tsman discusses some of these problems in his recent contributions to the journal, Hydrotechnical Construction.

Need for Investigation

4. Much concern was created among design engineers in Germany and the USSR because some measurements on completed U-shaped structures revealed earth pressures on the walls that were three times larger than those pressures assumed in the respective analyses. The possible reasons given were the horizontal movements of the walls due to temperature changes, water level changes inside the lock, and the ground-water-level fluctuations outside the structure, as well as the nonuniform compaction of the backfill material. On the other hand, no such pressure increases were recorded on some of the locks studied. This problem should be clarified, since it has a strong effect on the assumptions guiding the choice of an analytical model for locks.

PART II: SURVEY OF ANALYSES

5. The early analyses of lock-type structures are based on simple assumptions regarding the anticipated contact pressures, with no consideration for the stiffness properties of the soil and structures.

Early Analyses

6. An example of an early analysis is the presentation by Gromsch (1891). In 1906, Brennecke suggested that, depending on the anticipated conditions, the contact pressure at the base slab may be assumed as uniformly distributed or a linearly varying distribution with the vertex at the center. The pressure against the wall, due to water and/or soil, was assumed to be triangular. Based on this approach, Franzius (1908b, 1916, 1927) presented dry-dock analyses for a large variety of cases, which occur during dock construction and its operation upon completion. The analyses proposed by Engels (1921) were based on a similar concept. The pressure distributions used are shown in Figure 1.

7. In these analyses the choice of a pressure distribution is intuitive and it must satisfy only the vertical equilibrium, without regard to the properties of the soil and structure. Joppen (1952) attempted to prove that the

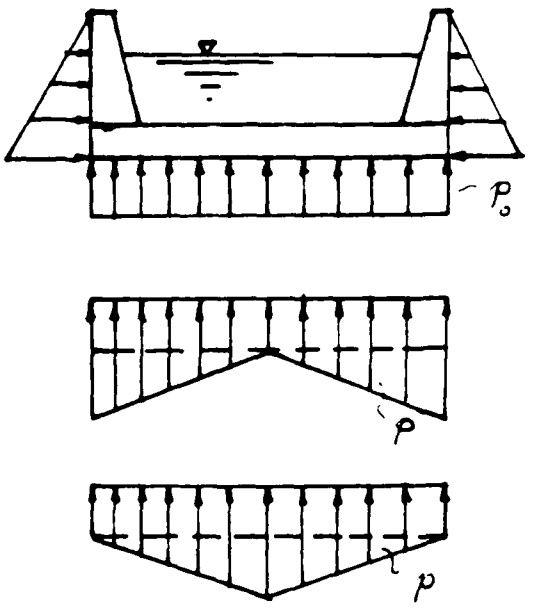

Figure 1. Assumed pressure distributions in early analyses

uniform contact pressure distribution is the critical one for design purposes. However, because of various misconceptions, his proof is not correct.

8. Analyses based on variations of the approach described above were suggested by Ellerbeck, as described by Pietrkowski (1929), and by Odenkirchen, as reported by Mugge (1940). For critical comments on the Ellerbeck method, refer to Ohde (1942).

9. More than a century ago Winkler (1867) published the differential equations for the continuously supported beam

$$D \frac{d^4 w}{dx^4} + kw = q(x) \qquad (1)$$

Solutions for specific cases related to railroad tracks were presented by Schwedler (1882) and Zimmerman (1888). These results suggested their use for the analysis of locks. Freund (1918) applied this approach for the analysis of a U-shaped lock structure by assuming that the vertical walls are "rigid" and subjected to water and earth pressure and the base slab is attached to a Winkler foundation, as shown in Figure 2. The first part of the paper (pp 84-104) covers the analytical approach, whereas the second part (pp 188-202) introduces an approximate graphical method.

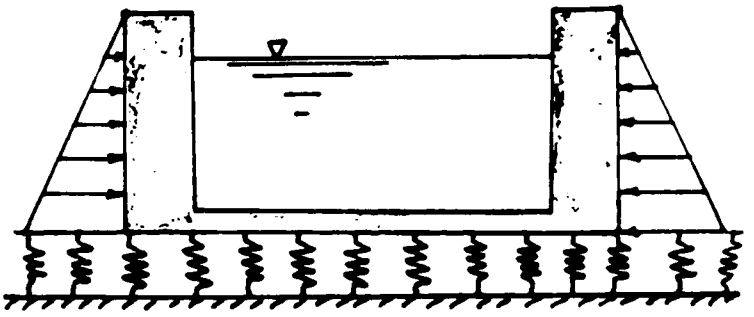

Figure 2. Analytical model used by Freund (1918)

10. Hayashi (1921) discussed the analysis of a U-shaped dry dock and presented a numerical example using the model shown in Figure 3. He also discussed a case when the center of the base slab may lift-off the ground (pp 154-158). The lock analysis by Zhemochkin (1927) was not available for review.

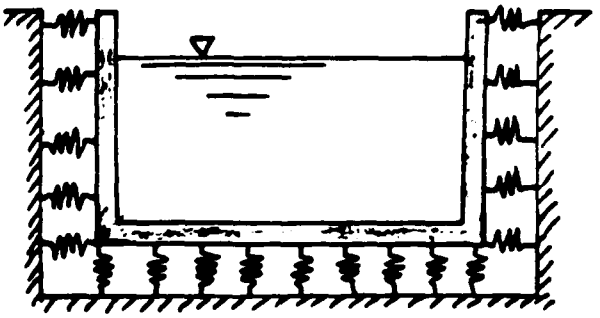

Figure 3. Analytical model used by Hayashi (1921)

11. Freund (1927), in a follow-up paper, first discussed the justification of the assumption that the soil responds elastically, and the methods for determining the coefficient of subgrade reaction k .* In this connection, he cited the test results by Muhlhofer (1922, 1923), Wolterbeck (1925), Moller (1921), and Franzius (1980a). A simplified analysis is then introduced, and the structure under consideration is classified as "short" (rigid), "finite," and "long" on a Winkler base.

12. The remainder of this paper is dedicated to an extensive analysis of the effect of vertical ground movements on the response of the U-shaped lock structure. The three types of ground movements discussed are: (1) settlements on one side only, (2) settlements on both sides, and (3) settlement at the center, as shown in Figure 4.

13. Another numerical example for analyzing a U-shaped dry dock, with the base slab modeled as a beam on a Winkler foundation, was presented by Beyer (1948).

State-of-the-Art Summary

14. In a treatise entitled "Analysis and design of dry docks and navigational locks," Agatz (1950) summarized the state-of-the-art in this area. The paper covers a large range of important topics and describes the

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* Of interest is the comment by Freund (1927, pp 76): "It is a pity that it is still not possible to establish the modulus of subgrade reaction k from Young's modulus E of the soil determined in a laboratory. This shortcoming should be taken into consideration in future soil and foundation investigations." For related results, refer to the recent paper "On the Determination of Foundation Model Parameters" by A. D. Kerr, Journal of Geotechnical Engineering, 1985.

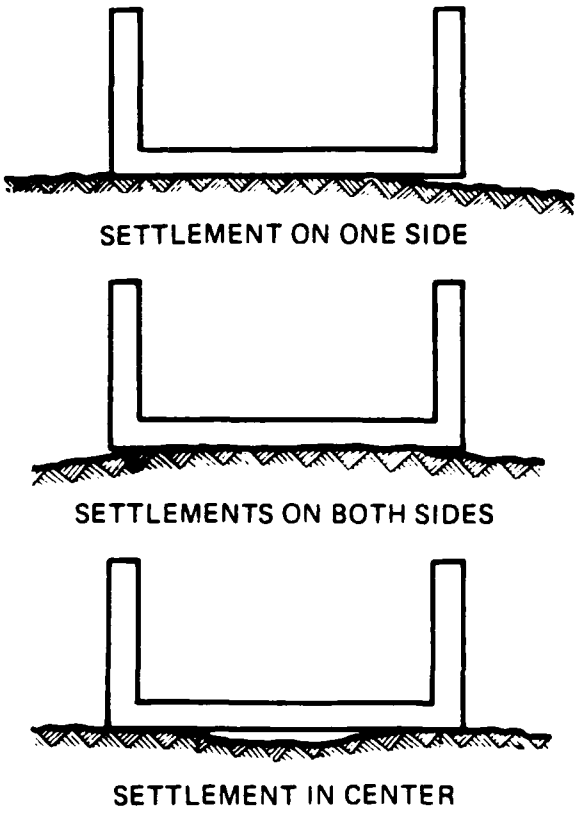

Figure 4. Ground movements discussed by Freund (1927)

experience gained from the many existing dry docks and navigation locks. Although no new method of analysis was proposed, the paper includes a discussion of various aspects that should be considered when analyzing dry docks and navigation locks.

15. The book by Press (1956) contains a description of various lock structures (with details of blueprints) and general guidelines regarding lock analyses (pp 293-298).

Analyses by Ohde

16. Still another method for the analysis of the base slab of a lock was presented by Ohde (1953). It is based on a number of assumptions, regarding the contact pressure distribution and the shape of the deformed slab (1942). It is a rather involved analysis which, because of the availability of the FEM and boundary integral methods, this method may not be very useful. The same comment applies to the base slab analysis presented by Kany (1959).

17. After World War II a number of lock-type structures were designed and built in the USA, West Germany, and the USSR. Since the planned structures were much larger than those built earlier, they revived questions regarding the sufficiency of the available analyses and codes. This, in turn, led to the initiation of a number of research projects with the aim of establishing the proper analyses for design purposes.

Analyses Used for the Port Allen and Old River Locks

18. In the USA the structures in question were the U-shaped Port Allen Lock, with a wall height of 21 meters, completed in 1961, and the Old River Lock, with a wall height of 24 meters, completed in 1963. The procedure followed was described by Clough and Duncan (1969) as follows:

> "In connection with the design of Port Allen Lock, the US Army Engineers conducted a review, described by Sherman and Trahan (1968), of existing procedures to determine the earth pressures acting on U-frame structures. All the methods reviewed had certain common features: (1) a plane section was analyzed; (2) wall pressures were assumed according to conventional earth pressure concepts; and (3) downdrag on the walls was neglected. Only in determining the base pressures were the methods different. A number of approaches involved the use of base pressure distributions determined by experience, but none of these approaches considered the required compatibility between the deflected base slab shape and the subsoil settlement profile. Analyses based on subgrade modulus concepts had been suggested as a means of satisfying the compatibility requirement, but this approach was not considered reliable in view of the difficulty in accounting for the effects of the backfill and the uncertainty in choosing an appropriate value of subgrade modulus.
>
> The method chosen for use in determining the base pressures for design of Port Allen Lock, and later Old River Lock, was a trial procedure in which soil deformations and base slab structural deflections were calculated for various assumed base pressure distributions. The correct pressure distribution was taken as that which yielded compatible structural deflections and soil deformations. This method thus satisfied the compatibility requirement and accounted for the soil compressibility, including time effects."

19. Because of the uncertainty of the used analyses, the docks were instrumented in order to record the earth pressures on the walls and base plate, the displacements, temperature distributions, etc. The instrumentation and results of the initial measurements were reported by Kaufman and Sherman (1964). They found that the distribution of the recorded base pressures differed substantially from the distribution assumed in the design analysis and that the observed wall pressures were generally lower than those used. It was also found that the downdrag mobilized at the lock walls produced moments at the centerline of base slab which were about 50 percent larger than those used in design.

20. An extensive report of the measurements on the Port Allen Lock was presented by Sherman and Trahan (1968) and on the Old River Lock by Sherman and Trahan (1972).

21. Because of the found discrepancies between the recorded data and the design analyses, the lock structures were again analyzed by using FEM modeling the surrounding soil as an elastic continuum. These results were reported by Clough and Duncan (1969), Duncan and Clough (1971), Clough and Duncan (1972), and Gould (1970). Since the initial calculations using linear constitutive equations were not satisfactory, the nonlinear equations proposed by Duncan and Chang (1970) were utilized. For the *chosen material parameters* the agreement of the calculations and measurement was good.

Recent West German Structures and Their Analyses

22. In West Germany the structures in question were the 16 locks needed for the Main-Danube-Canal, which were designed and built for three decades since the midfifties, as reported by Kuhn (1962, 1971). The lock wall heights vary. The ones of the Nurnberg-Sud Lock are 25 meters high, thus, slightly higher than the walls of the Old River Lock.

23. The designers of these locks also encountered the lack of reliable methods for estimating the expected earth pressures on the base slab as well as on the walls. The earth pressure on the walls was assumed, until then, as linearly increasing with increasing distance from the top. However, this assumption appeared questionable because of the flexibility of the tall walls. This was especially so, since the results of measurements on locks on the Volga River, reported by Tsarev and Feldman (1965), showed that the recorded

earth pressures might be three times higher than the calculated values.

24. This situation led to a number of research projects, as reported by Franke and Bernhard (1972), Sadgorski (1974), and Hilmer (1976). Hilmer, in his Dr.-Ing. dissertation, after briefly reviewing the earth-pressure assumptions used in Germany, presents results of an analysis with modified earth-pressure distributions, as shown in Figure 5.

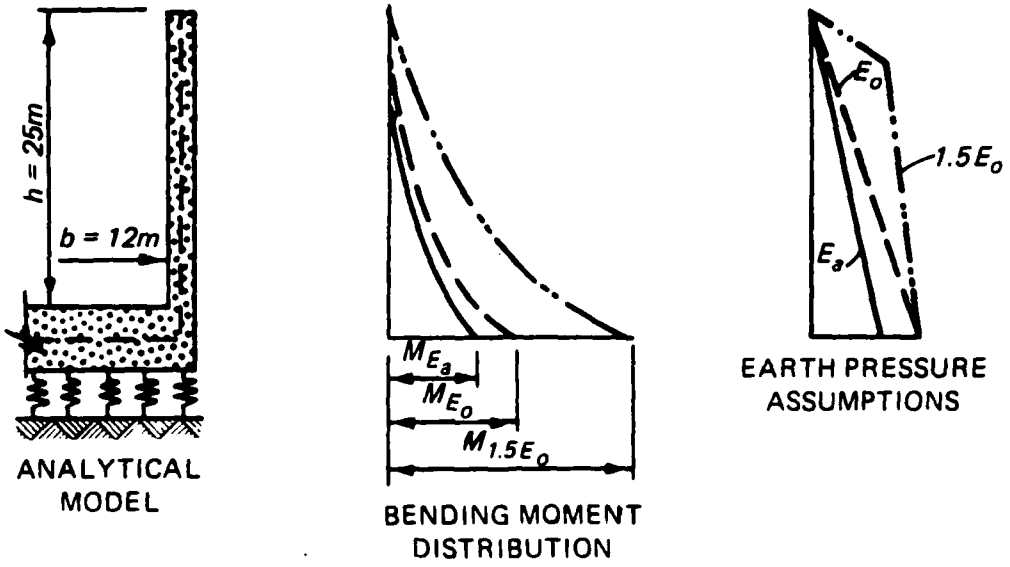

Figure 5. Modified earth-pressure distributions

25. The report by Hilmer (1976) contains a description of the test program on the Nurnberg-Sud lock and model tests conducted at the engineering schools in Nurnberg and Darmstadt. He utilized the Clough and Duncan (1969, 1972) FEM programs for an extensive parametric study of the Nurnberg-Sud Lock, using modified nonlinear constitutive equations by Duncan and Chang (1970) for the soil and linear response expressions for the concrete and steel rods.

26. According to Hilmer, the analyses pointed out the importance of taking into consideration the construction sequences when estimating the earth pressures and the displacement of the lock structure. It also showed that the temperature variations between winter and summer have a large effect on the earth pressures on lock walls that are over 15 meters high.

27. Hilmer did not observe the "stiffening" of the backfill material in the model tests and in some of the lock measurements. This was considered the reason for the substantial increase of earth pressures on some of the Volga locks as reported by Tsarev and Feldman (1965). This "stiffening" was

considered to have been caused by the cyclic horizontal movements of the lock walls due to the fluctuations of the water level and the annual temperatures in the chamber and the ground-water movements outside of the lock wall. This was suggested by Sinyavskoya and Pavlova (1971). However, on the basis of his findings, Hilmer accepts the explanation by Shcherbina (1974) that these earth-pressure increases were caused, instead, by a nonuniform compaction of the backfill. Note that a "stiffening" effect was also observed in the tests of the Luneburg ship-lifting facility, as reported by Schuppener (1975), and much earlier by Ohde (1948). This problem requires clarification.

28. In his concluding suggestions, Hilmer points out two essential loading cases for lock analyses: (1) due to earth pressure, when chamber is empty, and temperature increases inside of chamber; this case should yield the largest tensile stresses on the outer surface of lock wall, and (2) due to earth pressure, when chamber is filled, and temperature inside chamber drops; this case should yield the largest tensile stresses on the chamber side of the lock walls.

Lock Analyses in the USSR

29. In the USSR the intensification of research on the analyses of lock-type structures was apparently caused by planned revisions of the corresponding codes (SNiP II-I.10-65, SN 303-65, and SN 349-66) in the 1970's. A main problem with the old codes was the lack of reliable methods for the analysis of the earth pressure on vertical walls. This, according to the Editor's Note to the paper by Gol'tsman (1975), led to an "...increase in the consumption of reinforcement steel in structures being designed, in comparison with the consumption in older structures which are operating successfully." Thus, the lack of generally accepted methods for estimating earth pressures is similar to the situation encountered in the USA and West Germany.

30. According to the USSR code SNiP II-I.10-65 entitled "Retaining Walls of Hydraulic Structures" (in Russian) published by Stroizdat in Moscow during 1966, when the wall displaces toward the backfill, caused by external loads or temperature effects, the determination of the resulting (passive) earth pressure is to be calculated using the model of a beam on a Winkler foundation with a constant modulus along the wall height. It is also

mentioned that the foundation modulus, when justified, may be assumed as varying. Also of interest are the relevant sections in the book by Dubrova (1963).

31. A major effort then followed to establish the variation of the foundation modulus with wall height. The results of various research activities were reported by Gol'tsman (1975), Gol'tsman and Sheinman (1976), Gol'tsman (1977), and Bugrov (1978). Of special interest is the paper by Gol'tsman (1977) entitled "Strength Analysis of Dock-Type Lock Chambers and Retaining Walls" where the various methods of analysis used in the USSR are discussed.

32. When analyzing lock-type structures, the problem of uplift pressure must also be considered. In this connection, the publications by Sokolov and Logunova (1977), Marchuk (1979), Petrashen (1981), and Fishman (1982) should be noted.

PART III: SURVEY OF TESTS

Field Tests in Germany, USA, and USSR

33. Results of early tests on two dry docks were described by Franzius (1908a) while more recent studies on a lock-type structure conducted in Germany were reported by Schuppener (1975). Of special interest is the observed increase of the lateral earth pressure on the walls caused apparently by the horizontal movements of the walls. Other test results were described by Hilmer (1976).

34. Test results in the USA on the Port Allen Lock and Old River Lock were reported by Kaufman and Sherman (1964), Sherman and Trahan (1968), and Sherman and Trahan (1972).

35. Extensive field test programs on constructed structures were also conducted in the USSR. They were reported by Tsarev and Feldman (1965), Burmistrov and Kotenkov (1967), Sinyavskaya and Pavlova (1971, 1972), Mikhailov and Avdeeva (1973, 1974), and Nefedova and Kotenkov (1973).

36. As discussed in paragraph 23, the measurements of Tsarev and Feldman (1965) caused special concern among the design engineers, since some of the recorded earth pressures on the lock walls were three times higher than the values assumed in the analyses.

Reports Translated and Published

37. Four of these Russian papers were translated into German and were published by Smolczyk, Pertschi, and Hilmer (1976). This publication also includes the German translation of the USSR Code SN 303-65 "Guidelines for the Planning of Navigational Locks" published by Stroizdat in Moscow in 1966.

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* Hydrotechnical Construction is the title of the English translation of the journal Gidrotekhnicheskoe Stroitelstvo, Plenum Publishing Corp.

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